LIGO-I Science Goals and the LDAS Design

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Science Goals & Assumptions

- LIGO Goals, from LSC Data Analysis White Paper
  - » Test relativistic gravity
  - » Develop and exploit GW detection as an astronomical probe
- Data Analysis Assumptions:
  - » LIGO (and GEO, VIRGO) bring GW detection into region where it is plausible to detect astrophysical sources. They extend:
    - – amplitude sensitivity by factor 100-1000 (space volume 10^6 - 10^9)
    - – bandwidth by factor of 100
  - » *However:* there are no known sources with rates/amplitudes large enough to guarantee detection with LIGO-I,
  - » "Well understood" sources are probably too weak for LIGO-I
  - » There are large uncertainties in rate/amplitude estimates

No body of prior knowledge/best practice (as in HEP)

Opportunistic Data Analysis Strategy

- Initial emphasis is breadth (not depth)
  - » Instrument “broadband”, not tuned for particular source type
  - » Computing resources shared between different GW source types, not targeted at a particular type
- Have ability to recognize unanticipated sources
- Set upper limits on (among others)
  - » Rate of NS/NS, NS/BH, BH/BH binary coalescence
  - » Correlated GW emission by GRBs (Gamma Ray Bursts)
  - » Amplitude of GW emission by known pulsars
  - » Energy-density in the GW stochastic background
  - » Spatial density of nearby strongly GW-emitting pulsars
  - » Rate/amplitude of generic “burst-type” sources

Testing General Relativity

- GW emission during BH formation tests strong field gravity (near BH horizon)
  - » At late times, a sum of quasi-normal modes (l,m,n=1,2,3,…)
  - » Mode frequencies/damping times determined by mass & spin of BH
  - » Einstein's theory predicts n>1 mode frequencies from n=1
  - » Would give strong constraints on GR
- GW emission from CW sources (pulsars) tests spin-2 nature of GR
  - » 3 detectors sensitive to different linear combination of polarizations
  - » GR predicts how these will vary (and absence of spin-0 and spin-1)
- GW detection of burst sources seen electro-magnetically tests propagation speed=c in GR

Essential GW Searches (1)

- Binary Inspiral (pair of compact stars): either observe, or place upper limit on the rate in the Universe
  - » NS/NS well understood (a premiere LIGO design goal)
    - – Waveform can be calculated very accurately
    - – Hulse-Taylor binary (wrong freq for LIGO) is canonical example
    - – Hundreds of NS pulsars are cataloged
  - » NS/BH might offer much stronger signals for 20 solar-mass BH, but
    - – Rate "more" uncertain
    - – Waveform not calculable analytically (or numerically, currently)
    - – Signal processing strategy less certain
  - » BH/BH even more speculative
- Approach: parallel MPI-based hierarchical seach: 10-100 Gflops drives compute requirements

Essential GW Searches (2)

- Continuous wave sources (e.g., rapidly rotating neutron stars with bumps on them)
  - » Known neutron stars probably too weak to observe with LIGO-I
  - » Data analysis “easy” for observed pulsars with known periods, spin-downs
  - » Data analysis “difficult” for full-sky or partial-sky survey
    - – source waveform not single frequency (spindown)
    - – waveform modulated by earth’s spin, motion around sun, and Jupiter-induced perturbations
  - » Detector-limited search: Petaflops
  - » Practical search (factor of 2 less sensitive in amplitude): Teraflops
- Approach: hierarchical search, using off-site supercomputers/large beowulf clusters (or distributed grid: GriPhyN)

Essential GW Searches (3)

- Stochastic background signals
  - » Produced by early-universe processes (speculative) or unresolved "contemporary" phenomena
  - » A factor of 100 (or more!) smaller in amplitude than detector noise
  - » Analysis method: correlate signals from separated detectors
  - » Approach: "Easy" low bandwidth data analysis problem
- Gamma-Ray Bursts (poorly understood)
  - » At cosmological distances. Release huge amounts of energy
  - » Approach: correlate GRB catalog with GW burst catalog & h data
- Black hole formation
  - » Search for characteristic "ringdown" signal emitted by the perturbed horizon when BH is formed or enlarged by merger
  - » Tests Einstein's theory of GR
  - » Approach: trivial flops - use inspiral search code

Essential GW Searches (4)

- Close SN (Feeling lucky today? One/30-100 years.)
  - » Approach: plan duty cycle so one IFO is always in operation
  - » join the neutrino SN watch
- Optically observed supernovae
  - » Place limits on in-band signal
- Neutron stars formed in SN
  - » Rapidly rotating stars may have GW driven instability that spins them up and carries away large angular momentum in first year
- Unknown signals - for example previously undetected supernovae (unmodeled waveforms)
  - » Use time/frequency methods to add “events” to database
  - » Eventual early-warning for electromagnetic & neutrino observatories
  - » Approach: search for correlation between 2 or more sites

Impact on LDAS Architecture

- Easily parallelizable data analysis problems, with limited communications
  - » Beowulf architecture
- Low-latency (rapid) response & need to correlate analysis with on-site detector behavior
  - » On-site compute facilities
- More compute power & larger data sets needed for CW searching
  - » Larger off-site compute facilities
- Need to correlate data sets from different detectors
  - » off-site data archive and event data-base

Organization of Design & Coding

- LDAS Infrastructure: LIGO team + some LSC help
- Source-specific coding to: LSC ASIS lead groups
  - » Hierarchical binary inspiral
    - – Cardiff: templates & gridding
    - – UW Milwaukee: filtering
  - » Continuous wave (pulsar)
    - – AEI: wide-area Hough transform
    - – UW Milwaukee: wide area FFT stack-slide
    - – Caltech: directed sources
    - – Michigan: discriminators
  - » Unknown source (blind)
    - – Cornell: power monitoring
    - – Cardiff: time/frequency transforms
  - » Stochastic background
    - – UT Brownsville: correlation statistic

The following three pages contain supplementary material, if time permits.

Details: Binary Inspiral Search (1)

- Experience: search through data-set from November 1994 40-m prototype (reprint available)
- Use matched filtering (FFTs to convolve signal with bank of templates)
- Speed: at LIGO downsample rate a 300 MHz AXP-21164 (0.6 Gflop) can do 300 templates in real time
  - » 10,000 templates for M>1 solar mass => 30 CPUs
  - » 500,000 templates for M>0.2 solar mass => 1500 CPUs
- Previous search non-hierarchical. A hierarchical search should be a factor of 3 to 5 more efficient.

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Details: Binary Inspiral Search (2)

Hierarchical framework should be usable with any parameterized set of waveforms (eg, ringdowns)

- Filtering code (UWM)
  - » Master/slave framework for testing filtering modules and determining thresholds for hierarchical cuts completed
  - » Filtering modules completed
  - » Preliminary integration with LDAS WrapperAPI underway
- Template generation & placement code (Cardiff)
  - » Taylor- and Pade-approximant inspiral waveform code for spinless case complete
  - » Template bank generation code underway

Details: wide-area CW search

FFT coherent/Hough incoherent/FFT coherent hierarchical code being developed at the Max-Planck Albert Einstein Institute (Potsdam)

- » Will also be used for GEO-600 experiment pulsar search
- » Overall design complete (relative costs of different approximations)
- » Demodulation code for combining short FFTs completed & tested
- » Transformation code for GPS-time to solar-system-barycente-time complete
- » Currently working on sky template-grid layout and Hough transform modules
- » Expect to report completed working code by August LSC meeting